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The hybrid model for precompound decay is applied to the calculation of neutron spectra following the ^{20}Ne and ^{12}C bombardment of ^{165}Ho at 220, 292 (^{20}Ne) and 300 MeV (^{12}C). Results are compared with experimentally deduced angle integrated spectra and with results of the Boltzmann master equation. Both models give excellent agreement with experimentally deduced spectra.

Predictions of precompound decay in heavy ion reactions were made a decade ago using both the hybrid and Boltzmann master equation (BME) approaches.[1] In recent years, energies of accelerated heavy ion beams have increased, and many precompound phenomena have been experimentally observed. The BME has been applied to interpret some of these reactions;[2] in particular, it has been very successful in reproducing the shape and absolute magnitude of neutron spectra from heavy ion reactions which were gated on central collisions (via evaporation residue or fission fragment coincidences).[3,4]

In this work we re-explore the hybrid precompound decay model, as contained in the nuclear reactions code ALICE.[5] We do this because we can now compare predictions using the previously suggested parameter sets[1] with experimental results, and with the somewhat more cumbersome BME. We will analyze experimental results of the Berlin group,[3,4] which have previously been analyzed via the BME.[5]

The hybrid model is formulated as:

$$\frac{d\sigma_\nu}{d\varepsilon} = \sigma_R \sum_{n=n_0}^{\bar{n}} \left[\frac{X_\nu N_{n-1}(U)}{N_n(E)}\right] \frac{\lambda_c(\varepsilon)}{\lambda_c(\varepsilon)+\lambda_+(\varepsilon)} D_n \qquad \text{(Eq. 1)}$$

where $d\sigma/d\varepsilon$ is the differential cross-section for emission of a nucleon of type ν, and σ_R is the reaction cross section. The term in the first set of square brackets represents the number of nucleons of type ν at energy ε, such that on emission, the residual excitation energy would be U, with a composite nucleus excitation of E. The second set of brackets represents the ratio of emission ($\lambda_c(\varepsilon)$) to emission plus spreading rates for the nucleons at energy ε. The D_n represents the fraction of the population which has survived prior nucleon emission. The parameter n represents the number of excitons which are assumed to share the initial composite nucleus excitation energy in a random, equal a-priori probability fashion, where:

$$N(E) = \frac{(gE)^{n-1}}{p!h!(n-1)!} \qquad \text{(Eq. 2)}$$

with p and h the number of excited particles and holes, and n=p+h.

Following earlier suggestions,[1] and results found to be satisfactory with the BME,[6] we assume that n_0 is equal to the projectile mass (with the distribution of nucleon energies resulting from coupling the Fermi motion with the projectile velocity) and we evaluate the spreading rate, $\lambda_+(\varepsilon)$, from the average (Pauli corrected) collision rate of a nucleon of energy ε in nuclear matter.[7]

These parameters were used in the code ALICE to calculate neutron spectra for the reactions of 220 and 292 MeV ^{20}Ne and of 300 MeV ^{12}C on ^{165}Ho targets. Results are shown in Figs. 1 and 2, compared with the experimental results of the Berlin group and with results of the BME.

The experimental angle integrated spectra were obtained by fitting an assumed moving source to the high velocity neutron data, and angle integrating emission from the fictive source. The evaporation neutrons are therefore excluded in the experimentally deduced spectra shown in Figs. 1 and 2, whereas they are included in the ALICE result. The bars shown with the experimentally deduced points of Fig. 2 represent the range of results thought to encompass the true angle integrated spectrum, and do not represent random errors. Thus, the experimental results might better be represented as a grey band between the maxima and minima of the uncertainty bars of Fig. 2. Similar uncertainties exist for the experimental results of Fig. 1.

It is seen in the comparisons that the hybrid and BME models both reproduce the experimental spectra extremely well both as to magnitude and slope. These results suggest that the hybrid model and code ALICE may be a good predictive and/or interpretive tool with respect to precompound nucleon emission in central heavy ion collisions.

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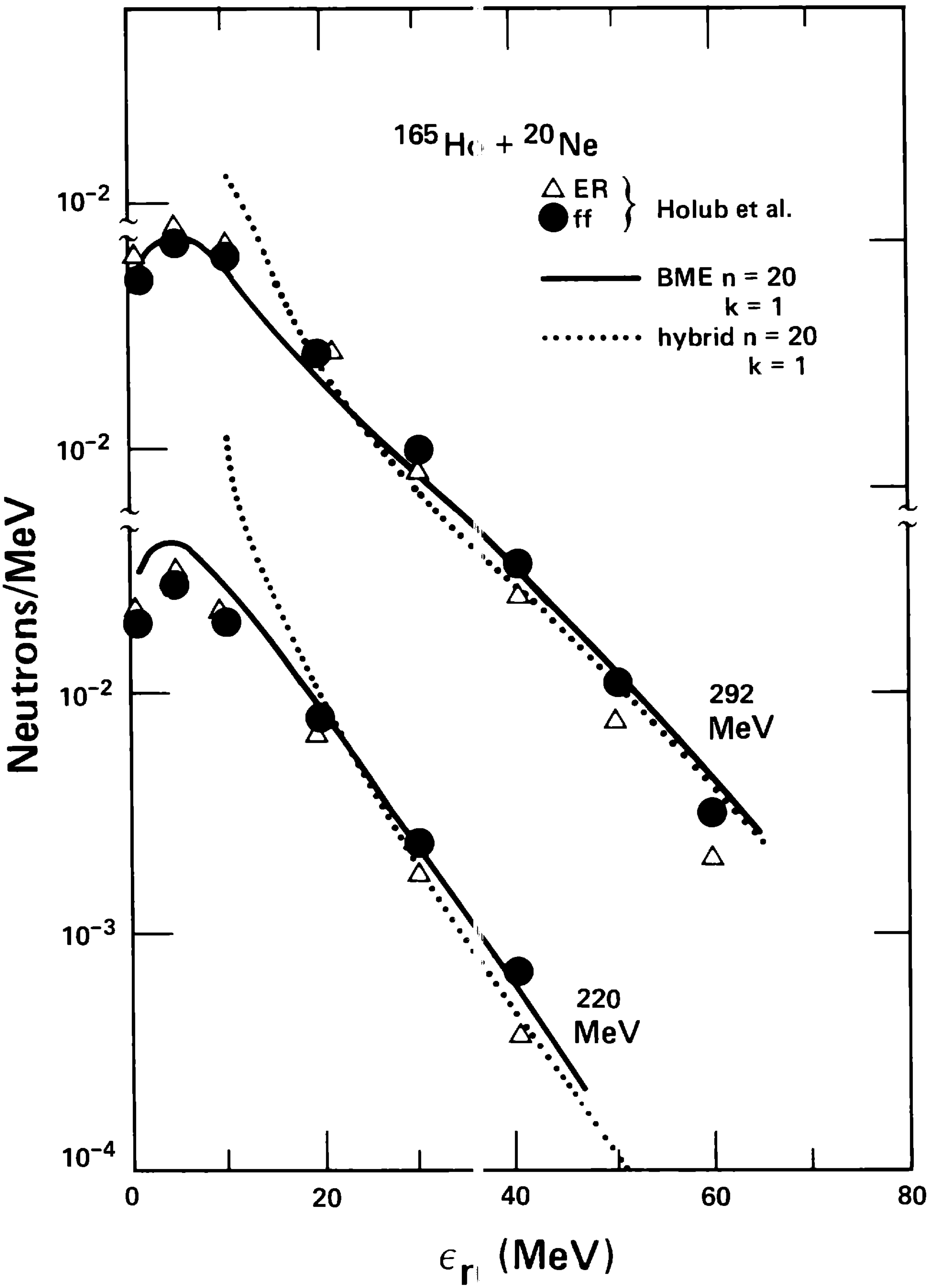
Figure Captions

Figure 1 Neutron spectra from the reaction $^{20}Ne+^{165}Ho$ at 220 and 292 MeV beam energy. The open triangles and closed circles represent evaporation residue and fission fragment gated spectra from Ref. 3. The dotted curve is the result of the hybrid and evaporation model result from code ALICE, and the solid curve is the result of the BME.

Figure 2 As in Fig. 1, for the reaction $^{12}C+^{165}Ho$ at 300 MeV. Experimental results are from Ref. 4.



^{165}Ho + ^{20}Ne
△ ER
● ff
Holub et al.
BME n = 20
k = 1
hybrid n = 20
k = 1
292
MeV
220
MeV
Neutrons/MeV
10^{-2}
10^{-2}
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
80
ϵ_n (MeV)

Figure 1

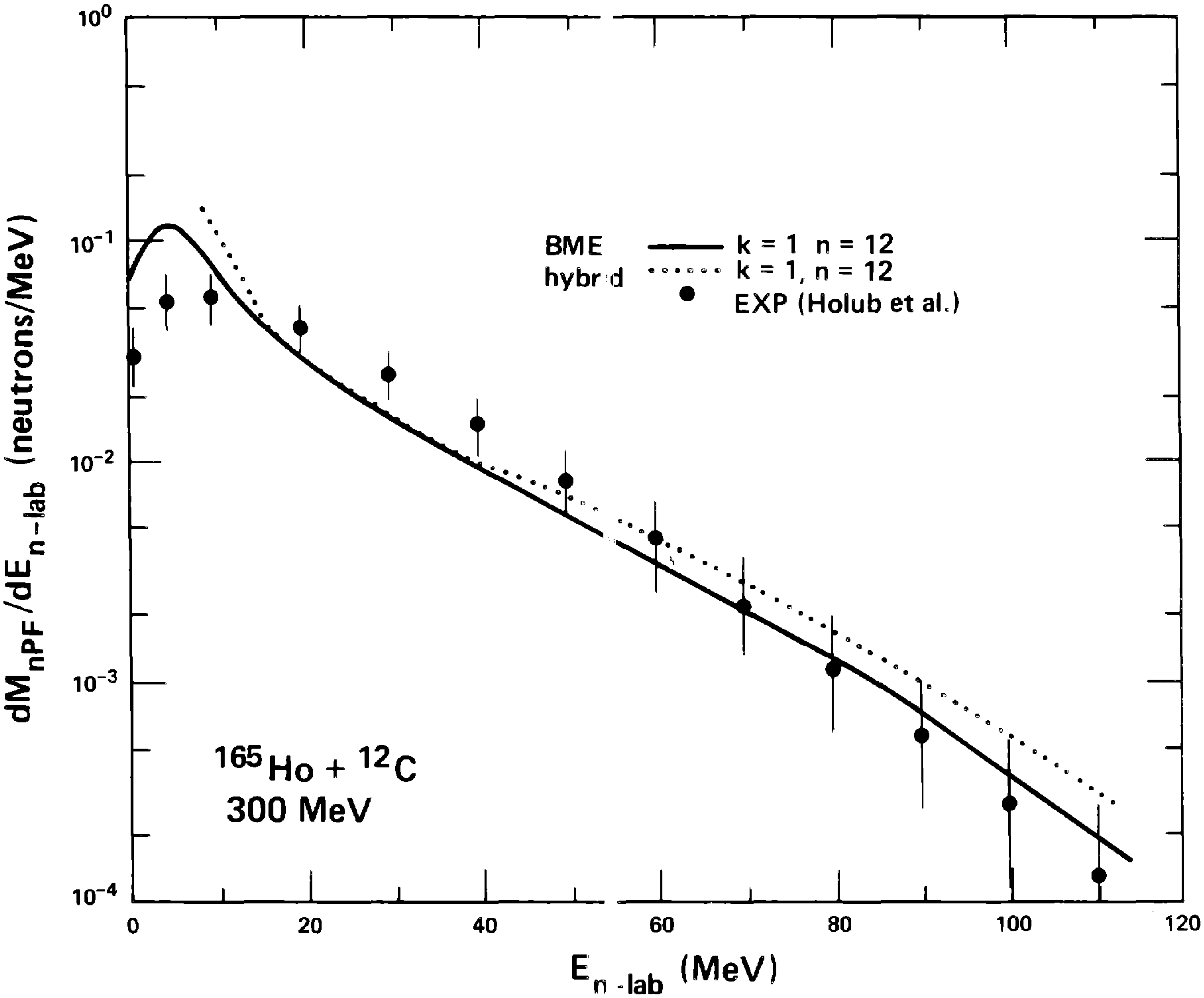

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
80
100
120
dM_{nPF}/dE_{n-lab} (neutrons/MeV)
E_{n-lab} (MeV)
BME
hybrid
k = 1 n = 12
k = 1, n = 12
EXP (Holub et al.)
$^{165}Ho + ^{12}C$
300 MeV

Figure 2